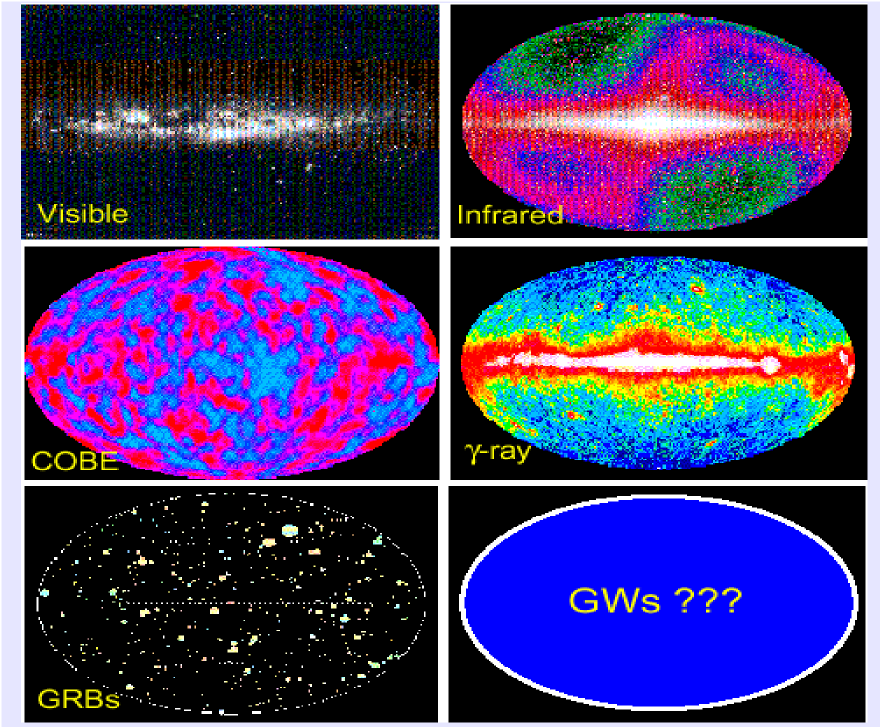
The Making of LIGO

Fred Raab,
LIGO Hanford Observatory,
on behalf of the LIGO Scientific Collaboration

7 Apr 2008

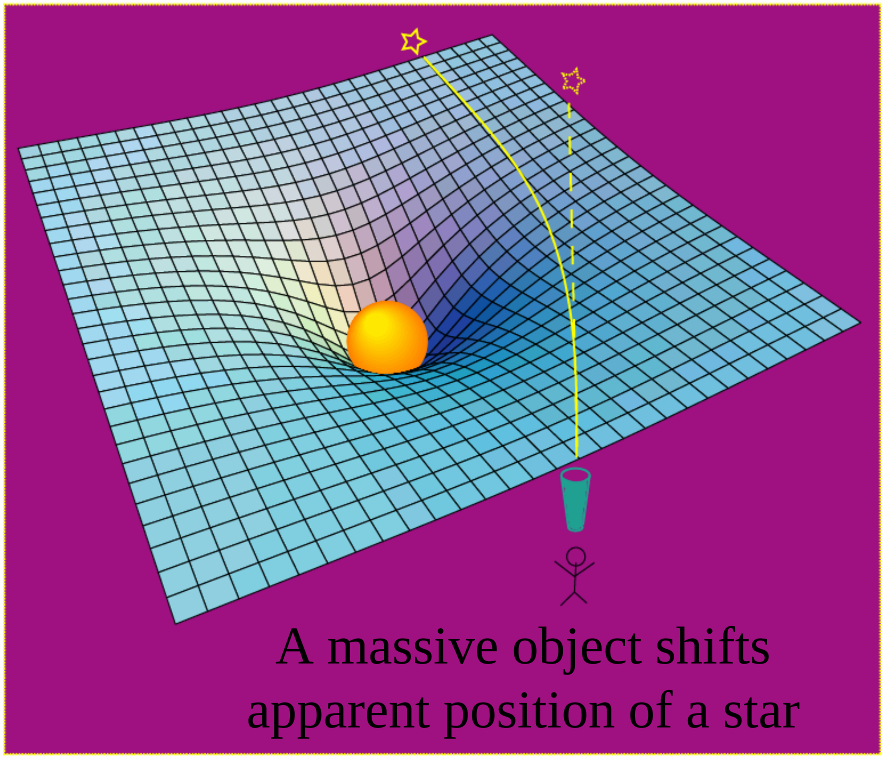


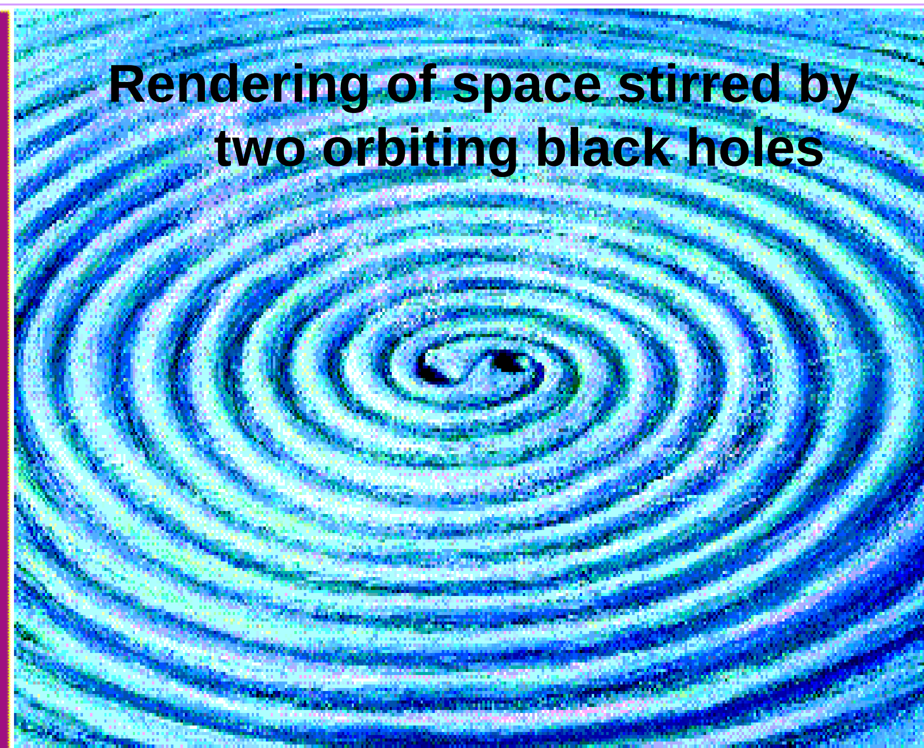
LIGO-G080186-00-W

Laser-Interferometer Gravitational Wave Detectors

- *Basic Idea*
- *Proposing LIGO*
- *Building the project*
- *Building a collaboration to do the science*
- *Making Initial LIGO work*
- *Moving toward Advanced LIGO*

Principle of Equivalence + Special Relativity $\Rightarrow$ Gravitational Waves





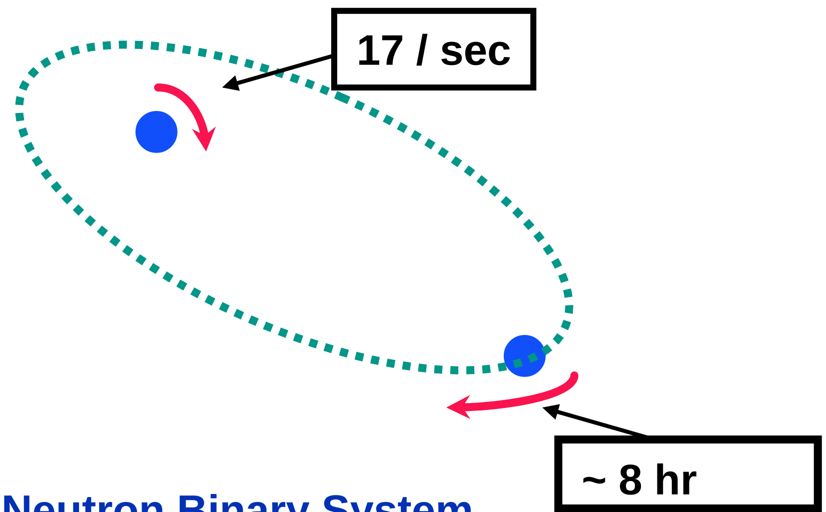
Changes in space warps produced by moving a mass are not felt instantaneously everywhere in space, but propagate as a wave.

Gravitational Waves
known to exist, just hard to find

Emission of gravitational waves

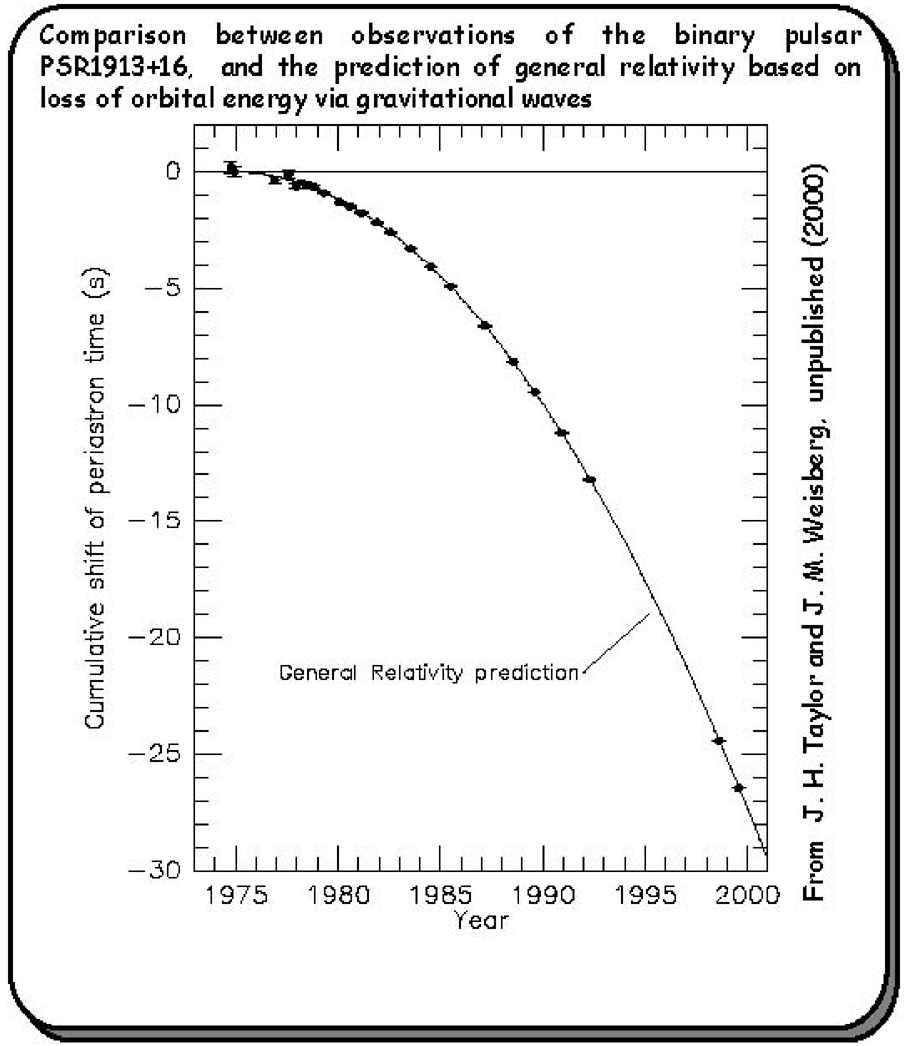
Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

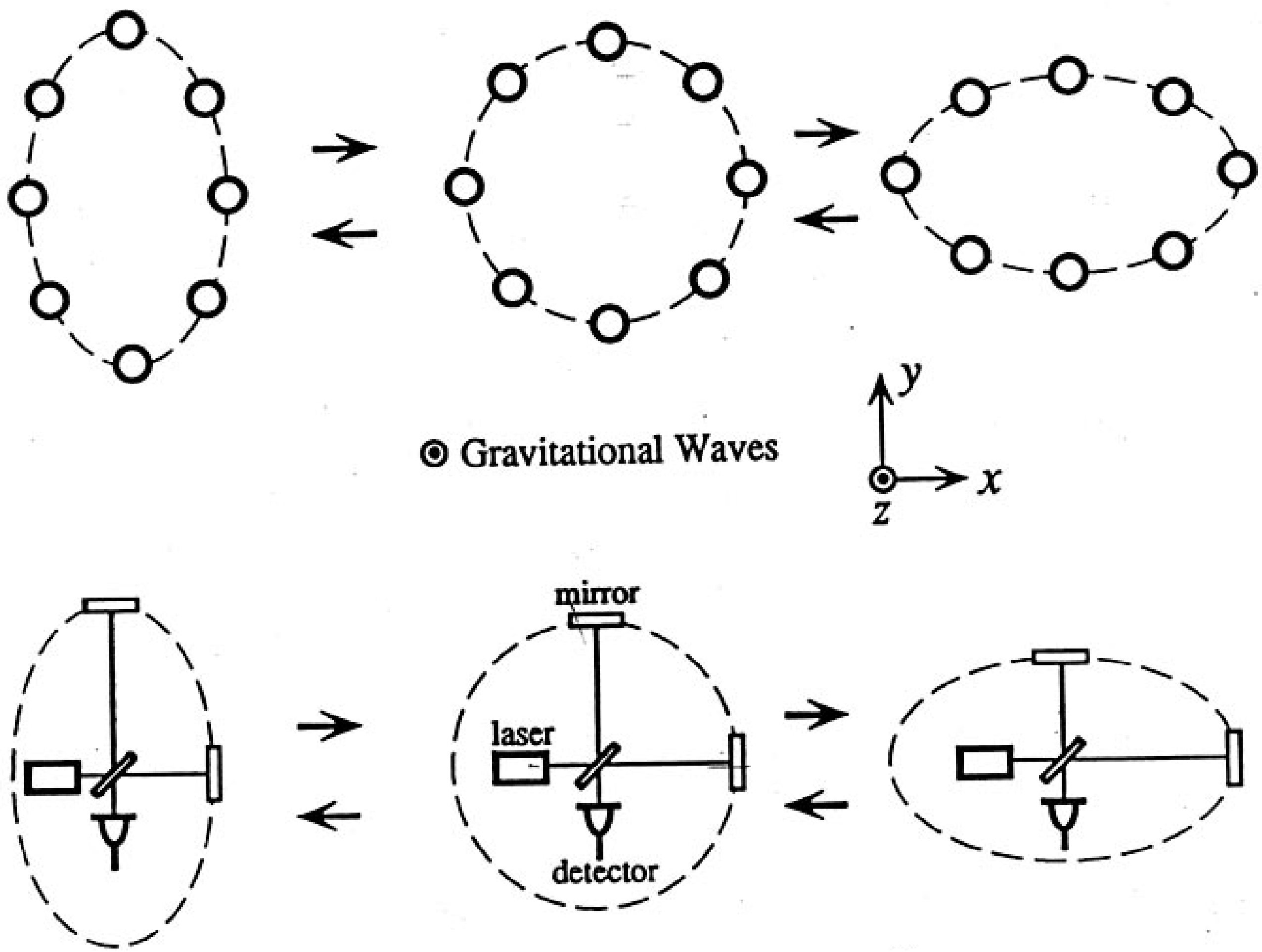


Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**



Gravitational waves deform a circle of space into an ellipse



Issues to address in 1989 proposal to build a gravitational wave detector

- Signal has never been detected
- Either source strengths or understanding of source populations ranges from “not well” to “poorly” known
- Simple arguments based on available information indicate that need to cover a space-time volume at least billions of times larger than previous detector searches to be in the ballpark
- Need to scale up size 100-fold from largest existing device
- Need to push frontier of measurement science, but no law of physics prevents it
- Any feasible detector using current or close-to-hand technology may not be sufficiently sensitive to make detections
- Very expensive: failure is not a viable option

Some of the technical challenges for design and commissioning

- ✓ Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- ✓ Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- ✓ Control km-scale arm lengths to 10^{-13} meters RMS
- ✓ Detect optical phase changes of ~ 10^{-10} radians
- ✓ Hold mirror alignments to 10^{-8} radians
- ✓ Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Do all of the above 7x24x365

✓ S5 science run 14Nov05 to 30Sep08

Building LIGO would be all about managing risk…

- Evolutionary approach:
  - » Build flexible facilities with growth potential and ability to house detectors of evolving configuration and performance
  - » Build world's first km-scale GW detector (Initial LIGO) to get into the ballpark; use only technology that could reasonably be delivered by time facilities construction ends.
  - » Conduct a technology development program concurrent with initial LIGO operations to advance what is possible for future detectors
  - » Evolve technology toward construction of Advanced LIGO detectors; hitting home runs might require increasing the space-time volume another factor of 1000-fold
- Tell the truth
  - » LIGO would be a long-term, high-risk, high-return undertaking
  - » Judge us on performance of detectors and management of resources; realize that making the sources is above our pay grade

Building the project…

- Special challenges:
  - » Grow a bunch of table-top experimentalists with the physics expertise into a project that can successfully build a monumental, frontier science facility
  - » No one ever built anything like it before, so can't ask what lessons were learned from the previous project
  - » Much larger than previous projects within NSF
- Fortunately for LIGO, demise of SSC made expertise available from building large particle accelerators and detectors

Some useful project strategies

- Hierarchical project structure with close coordination (dual nooses) for engineers and scientists leading sub-sytems
- Clear and manageable interfaces (elbow room inside subsystem; workable treaties with neighboring subsystems)
- Facilities construction would cost more than detector instrumentation, so first priority was to confine these risks
  - » Move quickly to minimize standing-army costs
  - » Conventional facilities initially de-scoped with remainder put into "contingency" to be built after most risk was retired from project
- Project assumed risks that could never be affordable to vendors for never-been-done items; specified processes, developed with vendors, not results
- Rapid performance measurement and communication to catch problems early and correct
- Retire standing armies as rapidly as possible

Selection of two observatory sites

- Published request for site proposals, including detailed specification of requirements
  - Scientific/technical
  - Construction cost drivers
  - Regulatory and availability cost drivers
  - Community-related drivers
- Received 19 proposals from 18 states
- Panel reviewed proposals and derived a short list of optimum site pairs
- NSF director made final selection

The LIGO Observatories

- **Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov**
- **NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).**

The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Owned by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 580 LIGO Scientific Collaboration members worldwide. Now engaged in joint operations with Virgo.

Building the collaboration to do the science

- Panel chaired by Boyce McDaniel looked at whether a high-energy physics collaboration or an astronomy model for data would optimize NSF's investment
- Recommended analysis by a collaboration of expert workers, but that entry into collaboration should be open
- LIGO Laboratory, comprising Observatories and Caltech & MIT support groups, operates LIGO for NSF
- LIGO Scientific Collaboration (LSC) is an open organization of scientists who receive data in exchange for labor toward collaboration goals; groups are funded separately from Lab
- LSC coordinates all scientific work and procedures govern membership and publications

LIGO Scientific Collaboration: how it works

- LIGO Directorate: Executive Director and Deputy Director of LIGO Lab + Elected Spokesperson of LSC
- Institutions join LSC by negotiating MOU with Lab and petitioning LSC to become members
- Member institutions have proportional representation on LSC Council (semi-annual mtgs); executive committee meets monthly for interim business
- Working groups (analysis, instrumentation, education) carry out collaboration work as captured in white papers
- Progress of institutions on MOU and work plans reviewed annually

Operating LIGO

- Caltech has fiduciary responsibility; MIT research group operates on subaward
- LIGO Oversight Committee appointed by Caltech and MIT provides joint institutional management
- Business and regulatory functionalities reside at campuses; Caltech subject to additional state laws for Observatories
- Observatory management (head, manager & administrator)
  - » Direct all work on site
  - » Coordinate with Caltech business systems
  - » Represent LIGO with regional entities

Nature of work in operations

- Scope of work
  - » Observatory operations
  - » Data analysis
  - » Instrumentation R&D
  - » Business
  - » Education
- Relatively flat management structure to promote high level of horizontal collaboration
- Matrix organization used to fit lean staff to varied tasks
  - » Single personnel supervisor at home site coordinates personnel with task leaders
  - » E.g., observatory operators also provide maintenance and assist science and engineering staffs with observatory tasks and broader tasks in instrumentation and analysis

Special considerations

- Safety
  - Normal issues + laser safety component + large number of visitors
  - Clear lines of responsibility
  - Work permit system
  - Weekly staff safety meeting
- Cybersecurity
  - Secure critical systems
  - Provide access to large collaboration with minimal hindrance
  - Need to be adaptive and reconfigure older solutions
- Education and Public Outreach
  - Science requirements placed observatories in rural settings with significant needs and under-served populations
  - Large opportunity
  - Large attendance

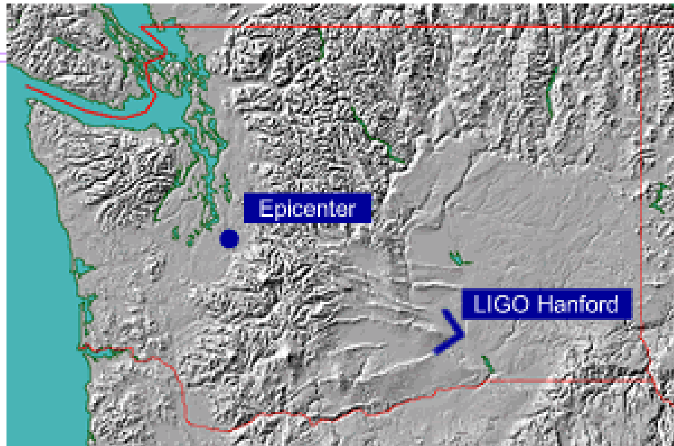
Facilities & infrastructure

- Special campus facilities
  - Optics, engineering, data archive & computing clusters
  - interferometer test beds for R&D through full-scale component test
- Observatory facilities (Hanford example)
  - 5.5 miles of paved access roads, water and waste systems
  - 65,000 sq ft of HEPA filtered laboratory space
  - 10 buildings, many specialized labs
  - One of the world's largest vacuum systems (10 ML over 8 km, 0.5 ML of LN2 storage, >100 pumps, 500 sensor/actuator points)
  - Interferometer controls, comprised of >100 high performance servo-control systems/machine, plus environmental monitoring (122,000 control points, 8500 operators screens, 142 computers, 350 custom analog boards, 300 commercial boards)
  - 1 TB/day data collection, 48 TB disk cache, 128 TB tape robot
  - Online data analysis and archiving center (420 processors, 1T-flop)

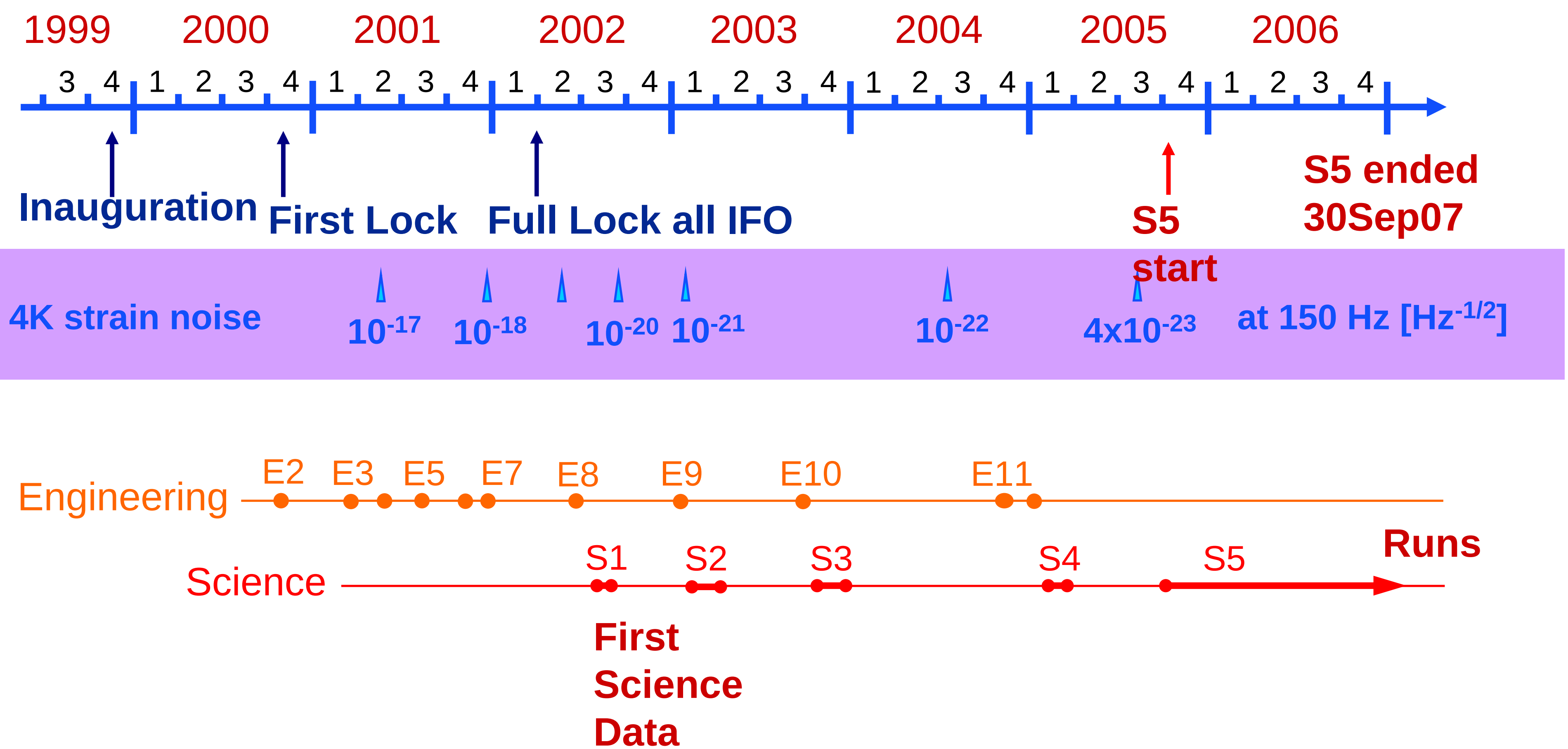
Staffing

- ~150 staff overall in LIGO Lab
  - » 10% business/directorate
  - » 40% engineering/technical/management
  - » 20% staff science (R&D, commissioning, management)
  - » 30% postdocs & grad students
- ~ 30 staff for operating each observatory
  - » ~1/3 Ph.D. level physicists
  - » ~1/3 Special engineering or technical support
  - » ~1/3 Operators
  - » typically 6-12 technical visitors
  - » ~4000/yr public visitors

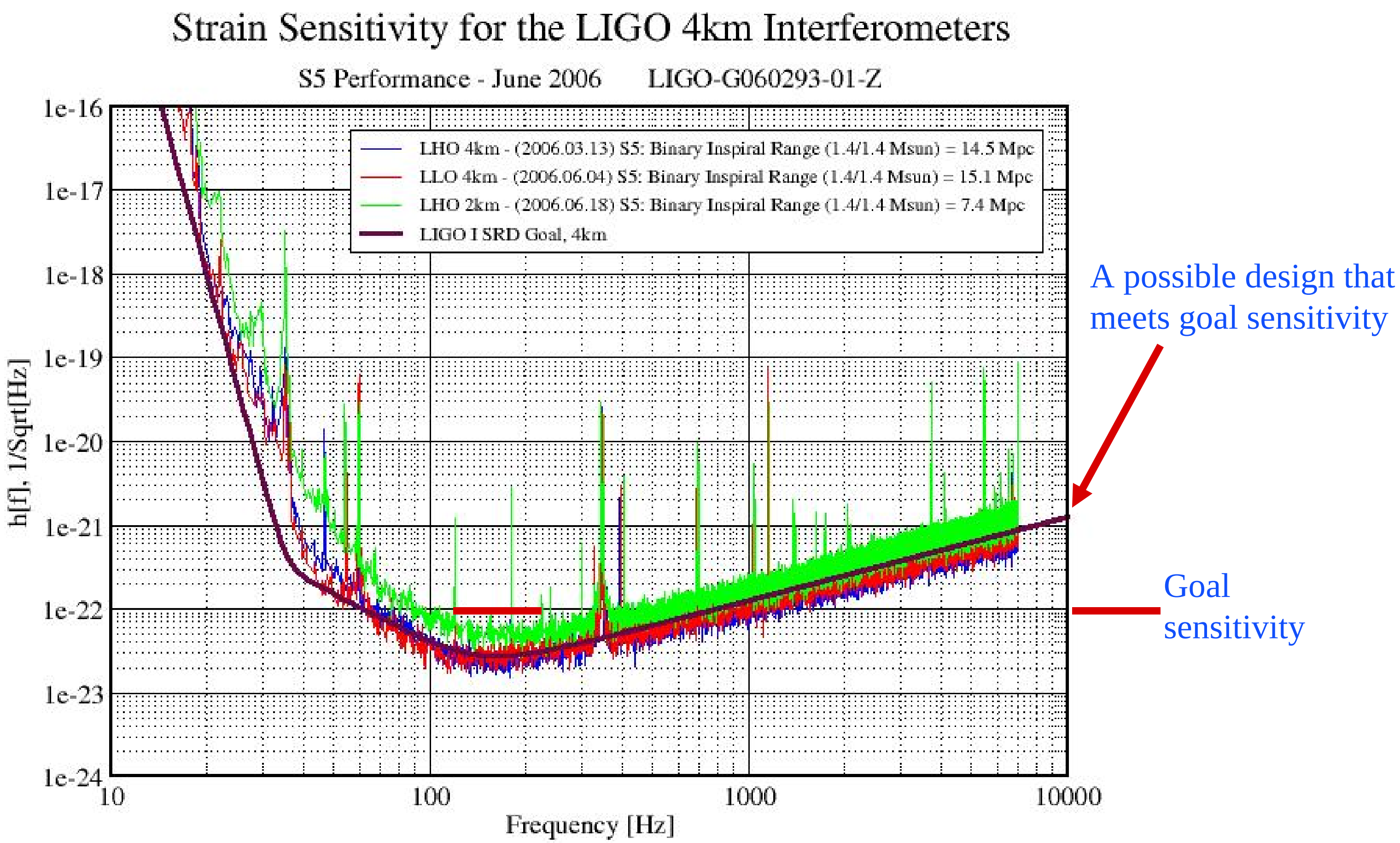
Despite a few difficulties, science runs started in 2002.



Commissioning and Running Time Line



Initial LIGO detectors are working to 1989 design goals



Science to date

- No published detection yet, but ~30 papers based on search data interpretation, such as
  - » Limit on %-age of energy emitted by Crab Pulsar going into GWs
  - » Limit on GW background from early universe
  - » Limits on the ellipticities of known pulsars
  - » Limits on GW waves emitted by GRBs and SGRs
  - » Limits on rates of mergers of black holes and neutron stars
  - » Determined that the short GRB070201, possibly in M31, was either a compact binary merger at much greater distance or a different source in M31, such as an SGR

Next challenge: building a project while maintaining operations

- Advanced LIGO project is now starting, even while
  - » Initial LIGO 4-km interferometers being enhanced to improve performance for an S6 run
  - » AstroWatch observing program ongoing using Hanford 2-km instrument
  - » Data from prior runs in analysis
  - » Instrument R&D continues
  - » Education & Public outreach continues
- Requires interface of relatively flat operations structure with heirarchical project structure
- Operations will ramp down as experienced labor transitions to project and ramp up as project ramps down

Summary

- LIGO has successfully reached goals of initial project
- Operations have met challenges of different operational phases and is now mature
- Large international collaboration actively pursuing science and base-building for future of the field
- A global detector network is now in place, with coordinated observing and instrumentation upgrades
- Technical development program has succeeded to enable large increases in future detector performance
- Building Advanced LIGO detectors within an operating laboratory and collaboration is an exciting new challenge